32.3: Utilizing the Bi-Directional Reflection Distribution Function to Predict Reflections from FPDs

E. F. Kelley, G. R. Jones
NIST, Gaithersburg, MD

ABSTRACT: A method is presented which accurately predicts the reflected luminance from a flat panel display from known lighting conditions using the bidirectional reflection distribution function (BRDF) of the display. The BRDF model employed separates the reflection into three components: diffuse (lambertian), specular, and haze. Calculated values for the reflected luminances are compared to measured values for several lighting conditions with good agreement. Attempts to parameterize the BRDF of a flat panel display (FPD) are discussed.[*]

INTRODUCTION

The goal of this research is to establish a reflection model for the surface of an electronic display so that the reflection off the screen can be calculated given any surrounding luminance or lighting distribution. With such a model, the luminance characteristics of the display (such as contrast) can be measured in a darkroom, and then the performance of the display in any desired ambient lighting condition can be calculated. This can alleviate the necessity of creating difficult or expensive ambient lighting conditions in order to determine the performance of a display with reflections.

FORMALISM

The model is based on the bidirectional reflection distribution function (BRDF).[1,2] Neglecting any wavelength and polarization dependence, the BRDF is a function of two directions, the direction of the incident light (θ_i, ϕ_i) and the direction from which the reflection is observed (θ_r, ϕ_r) in spherical coordinates as shown in Fig. 1. The BRDF relates how any element of incident illuminance dE_i from direction (θ_i, ϕ_i) contributes to a reflected luminance dL_r observed from direction (θ_r, ϕ_r):

$$dL_r(\theta_r,\phi_r) = B(\theta_i,\phi_i,\theta_r,\phi_r)dE_i(\theta_i,\phi_i), \qquad (1)$$

where $B(\theta_i, \phi_i, \theta_r, \phi_r)$ is the BRDF. By integrating over all incident directions in space, the luminance $L_r(\theta_r, \phi_r)$ observed from any direction (θ_r, ϕ_r) can be determined by

$$L_r(\theta_r,\phi_r) = \int_0^{2\pi}\int_0^{\pi/2} B(\theta_i,\phi_i,\theta_r,\phi_r)dE_i(\theta_i,\phi_i). \qquad (2)$$

The illuminance contributions dE_i arise from luminance sources in the room. For each element of solid angle $dA_i/r_i^2 = d\Omega = \sin\theta_i d\theta_i d\phi_i$ at a distance r_i from the screen there is a source luminance $L_i(\theta_i, \phi_i)$ producing illuminance

$$dE_i = L_i(\theta_i,\phi_i)\cos\theta_i d\Omega, \qquad (3)$$

where the cosine term accounts for the spreading of the illuminance over a larger area as the inclination angle increases. Equation 3 expresses the concept of incident luminance.

Diffuse and specular reflection models are inadequate to characterize reflection from all displays. There is a third type of reflection that we will call haze, for want of a better term.[3] The diffuse reflection model for a lambertian surface relates the reflected luminance to the total illuminance by $L = qE$, where $q = \rho_d / \pi$, and ρ_d is the diffuse reflectance. Specular reflection is characterized in terms of the luminance of the source L_s and the specular reflectance ρ_s so that the reflected luminance is given by $L = \rho_s L_s$.

Many screens today have surfaces that disperse some of the specular light energy into other directions. Using a point light source (such as a bare flashlight bulb), if you can see a distinct image of the source in the reflection then the surface has a specular component. If you can see a general dark gray background that is relatively uniform across the screen then the screen has a non-trivial diffuse (lambertian) component. If you see a fuzzy light surrounding the image of the bulb then the screen also has a haze component. In fact, the BRDF can be obtained from a measurement of the reflection distribution from a point source, but space does not permit our detailing the process.

It is important to realize that not all components of reflection need to be observable. At least one component must exist, of course. There are displays that have entirely diffuse surfaces (e.g., white xerographic

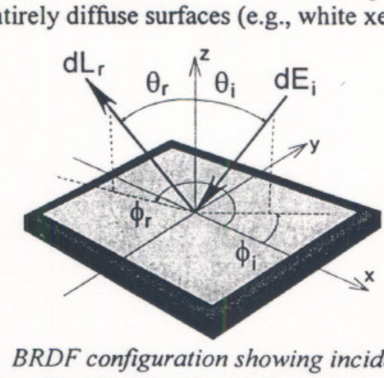

Fig. 1. *BRDF configuration showing incident and reflection directions in spherical coordinates.*

[*] *Electricity Division, Electronics and Electrical Engineering Laboratory, Technology Administration, U.S. Department of Commerce. This is a contribution of the National Institute of Standards and Technology; not subject to copyright.*

ISSN0097-0966X/97/2801-0831-$1.00 + .00 © 1997 SID

copy paper). There are displays that don't have a specular component and have only a haze component with the diffuse component being negligible (10^{-4} the size of the haze reflection). When the reflection of a light source is observed in such screens only a fuzzy patch of light is observed in the specular direction and no distinct image of the source is observed. There are displays that don't have a substantial haze component and only exhibit specular and diffuse reflections. Many television picture tubes are of this nature.

We can capture these three types of reflection explicitly with the BRDF formalism in terms of three additive components

$$B = D + S + H\,, \tag{4}$$

where the components are defined by

$$\begin{aligned} D &= q = \rho_d / \pi, \\ S &= 2\rho_s \delta(\sin^2\theta_r - \sin^2\theta_i)\delta(\phi_r - \phi_i \pm \pi), \\ H &= H(\theta_i, \phi_i, \theta_r, \phi_r). \end{aligned} \tag{5}$$

In the specular term the delta functions $\delta(\ldots)$ simply assure that the specular contribution only comes from whatever source may be located in the specular direction. When we integrate this three-component BRDF over all incident illumination directions by combining Eqs. 2-5, the reflected luminance is given by

$$\begin{aligned} L_r(\theta_r, \phi_r) &= qE + \rho_s L_s(\theta_r, \phi_r \pm \pi) \\ &+ \int_0^{2\pi} \int_0^{\pi/2} H(\theta_i, \phi_i, \theta_r, \phi_r) L_i(\theta_i, \phi_i) \cos(\theta_i) d\Omega. \end{aligned} \tag{6}$$

The first term is the familiar lambertian reflection where E is the total illuminance from all directions, and the diffuse reflection coefficient q is expressed in terms of the diffuse reflectance ρ_d by $q = \rho_d / \pi$. The second term is the specular reflection where the specification of $(\theta_r, \phi_r \pm \pi)$ simply selects the light from the viewing direction (θ_r, ϕ_r) reflected about the normal (z-axis), i.e., the specular direction associated with the viewing direction. The last term is the haze contribution.

Because the full BRDF is a four-dimensional function, to measure it completely would require a large amount of data and the measuring instrumentation would be expensive. However, we may be able to take advantage of some simplifications that reduce the amount of data so that this formalism is manageable. First, note that most displays are viewed from the normal direction (or at least from one direction), and the range of angles to observe the entire screen from the normal position are usually on the order of ±30°. For electronic displays, it is often found that the shape of the BRDF does not change appreciably over this range. Thus, a reduced BRDF $B(\theta_i, \phi_i) \equiv B(\theta_i, \phi_i, 0, 0)$ is adequate for most reflection characterizations. If the BRDF is seen to be symmetrical then the BRDF is independent of ϕ, $B(\theta_i, \phi_i) = B(\theta_i)$. For such a case,

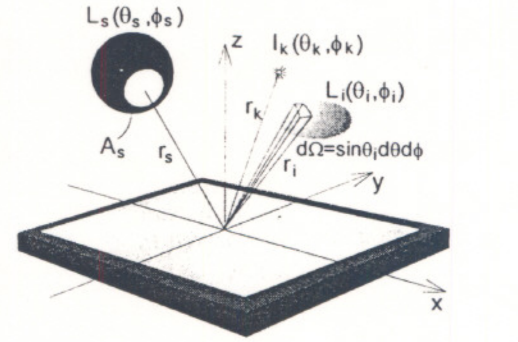

Fig. 2. *Three types of sources: discrete uniform source L_s, point source I_k, and distributed luminance L_i.*

acquiring a suitable BRDF for displays amounts to taking an in-plane BRDF where the detector is held near the normal of the screen and the source is rotated about the normal in the horizontal plane.

However, because of structure behind the front surface of the display, this last reduction is sometimes not possible, i.e., the BRDF is not always rotationally symmetric about the normal. In such cases several BRDF curves will have to be taken at selected angles ϕ_k and then combined to produce an approximate BRDF. If $B_k(\theta_i)$ represents the k in-plane BRDFs taken at discrete angles ϕ_k needed to characterize the reflection, the full BRDF might be represented by a sum of products

$$B(\theta_i, \phi_i) = \sum_k B_k(\theta_i) F_k(\phi_i)\,, \tag{7}$$

where the $0 \le F_k(\phi) \le 1$ mix the discrete planar BRDFs to approximate the true BRDF. For example, if the reflection haze of a point source is elliptical rather than circular, there would be two BRDFs needed, one for each of the axes of the ellipse, say, B_H for horizontal and B_V for vertical. The full BRDF could be expressed by

$$B(\theta_i, \phi_i) = B_H(\theta_i) F(\phi_i) + B_V(\theta_i)[1 - F(\phi_i)]\,,$$

where $0 \le F(\phi) \le 1$ such as $F(\phi) = \cos^2\phi$.

Regarding the luminance distribution in the surround, it may also be useful to consider three types of luminance sources: isolated sources of areas A_s that are a large distance r_s away from the screen with average luminances $L_s(\theta_s, \phi_s)$, point sources of luminous intensity $I_k(\theta_k, \phi_k)$, and distributed sources (such as a wall) $L_i(\theta_i, \phi_i)$. See Fig. 2. The reflected luminance from these sources is, extending Eq. 2 for the reduced BRDF,

$$\begin{aligned} L_r(0,0) &= \sum_s L_s(\theta_s, \phi_s) \cos\theta_s \frac{A_s}{r_s^2} B(\theta_s, \phi_s) + \\ &\sum_k \frac{I_k}{r_k^2} B(\theta_k, \phi_k) + \\ &\iint_A L_i(\theta_i, \phi_i) B(\theta_i, \phi_i) \sin\theta_i \cos\theta_i d\theta_i d\phi_i. \end{aligned} \tag{8}$$

The first term is useful for placing distant lamps at various angles around the screen and using single values of the BRDF to calculate the luminance.

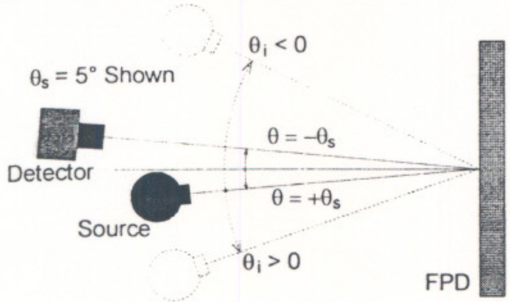

Fig. 3. Specular configuration for obtaining an in-plane BRDF. 5° configuration shown for clarity.

ACQUIRING SIMPLE BRDF DATA

Because the shape of the BRDF doesn't change appreciably for angles near the normal, we can set the detector at −3° to the left of normal and the light source at +3° to the right of normal—a specular configuration in the horizontal plane ($\phi = 0$)—see Fig. 3. Then the peak of the reflection at the specular angle can be measured. To calibrate the CCD camera for accurate luminance measurements, a diffuse reflectance standard is used having reflectance ρ_w whereby the counts from the pixels in the CCD can be calibrated against the luminance of the standard L_w measured in cd/m^2. The illuminance falling on the screen can also be measured using the standard $E_w = \pi L_w / \rho_w$.

The field of view of the detector and the diameter of the output of the light source are factors that influence the resolution of the BRDF measurement system. The delta-function behavior noted in Eq. 5 is ideal. In actuality, the sharpness of the specular peak measured depends upon how closely the lamp approximates a point source, how small an area is measured by the detector, and how wide the detector is. The wider the source or the wider the detector, the more any specular peak will be smeared out. Because of this delta-function behavior, we are exploring alternative methods to separate the specular peak from the haze peak. One method under study employs an illuminated area with a small black dot at its center to separate the specular and haze peaks.

The haze function is usually very peaked about the specular direction and best rendered on a logarithmic scale. It often covers four or more orders of magnitude for very black screens. In Fig. 4 we show a high-resolution BRDF for a material with a large diffuse component and with both a haze and specular component. Note the sharp specular peak on top of the haze. Note also the non-trivial background in the wings that represents the diffuse component according to the model expressed in Eqs. 4 and 5.

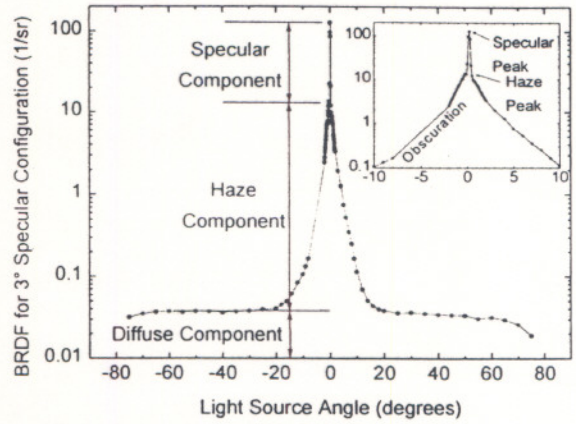

Fig. 4. BRDF of sample material with obvious diffuse component. Inset shows detail of peak. The resolution of the BRDF apparatus is 0.2°, and a point source is employed to obtain the BRDF.

RESULTS

We test this simplified BRDF model employing a screen with a symmetrical BRDF having only a non-trivial haze component—no specular and a very small diffuse component. We configure three lighting arrangements: (1) a 1.9 m diameter integrating sphere having a quasi-uniform interior luminance distribution centered on the display with the display normal centered in a 10 cm exit port in which case a fuzzy dark patch appears at the center of the screen, (2) the same sphere with the display rotated and (3) two uniform sources of 150 mm diameter on each side of normal 1 m away from the screen (we use the first term in Eq. 8 to calculate the luminance here). In all cases the luminance is calculated and measured at screen center. Case 2 is obtained by turning the display 5° to 10° from its orientation in case 1 so that its normal is no longer pointing out the exit port whereby the exit port has no effect on the measured luminance. See Fig. 5.

A stabilized helium-neon laser is used to measure the BRDF. A spinning clear plastic disk slightly coated with a transparent scattering material is em-

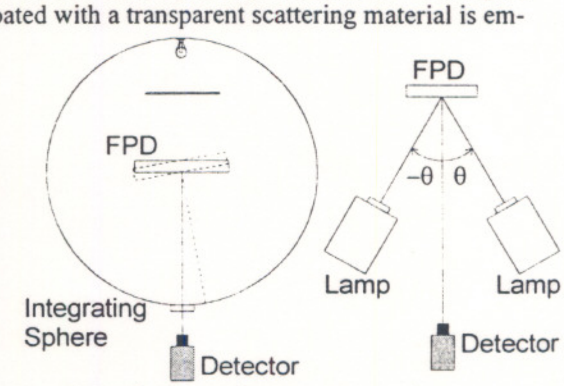

Fig. 5. Lighting configurations tested: integrating sphere with exit port and with display at 0° and 5°, two uniform light sources at ±θ.

ployed to reduce the speckle. Figure 6 shows the in-plane horizontal BRDF for the screen employed in the experiment. The scatter at the peak arises from an instability in the interaction of the laser beam and the active-matrix-liquid-crystal FPD used. The shape of the BRDF can be approximately fit with the following seven-parameter function shown as the solid line:

$$B(\theta) = \frac{h}{e-1}\left[\exp\left(\frac{w}{w+|\theta-a|^n+b|\theta-a|^m}\right)-1\right]+q, \quad (9)$$

where $h = 10.80\ \mathrm{sr}^{-1}$ is the height of the haze peak, $w = 7.05$ is a measure of its width, $n = 2.25$, $m = 4.51$, $b = 0.00105$, $q = 0.0025\ \mathrm{sr}^{-1}$ is the diffuse reflection coefficient, and a = 0.349° accounts for small alignment errors.

Using the BRDF data, the reflected luminance of the display can be calculated from the measured luminance distribution and compared with the measured luminance for each case. Table 1 shows the results. The agreement between the measured luminances of the screen and those calculated using the BRDF are mostly within 5%. No attempt was made to compensate for any veiling-glare corruption of the luminance measurements. Glare would especially affect the measurement of the reflected hole in case 1—its true value is probably lower than what is reported. We estimate that the luminance measurements have a combined standard uncertainty of ±5%, the uncertainty in the measurement of the BRDF in the vicinity of the peak is ±5%, and the uncertainty in measurement of the angles involved is ±0.5°—all with coverage factors of k = 2. (There is insufficient space to provide a full presentation of the error analysis.)

Table 1. BRDF Luminance Comparison (cd/m²)

Case	Measured	Calculated	Error
Case 1 Int. Sph. + Hole	49.8	46.6	-6.3%
Case 2 Int. Sph.	75.3	77.7	3.2%
Case 3 Lamps $\theta = \pm 25°$	0.153	0.148	-3.2%
$\theta = \pm 30°$	0.0890	0.0861	-3.3%
$\theta = \pm 35°$	0.0535	0.0527	-1.4%

CONCLUSION

The ultimate goal of this work is to provide a parametric representation of the BRDF if possible. The specular reflectance ρ_s and the diffuse reflectance ρ_d would be two parameters, and at least the height h and a width w of the haze peak would be required. The haze may also require some kind of a shape parameter as well in order to fit all display BRDFs. A measurement of the BRDF is impractical for most laboratories. However, should this parameterization scheme be adequate, then the manufacturer would only have to supply those parameters for a particular product-line of displays, and the user could set up simple lighting configurations to test the BRDF provided. Then the parameterized BRDF could be used to calculate the reflection properties of the screen in any environment.

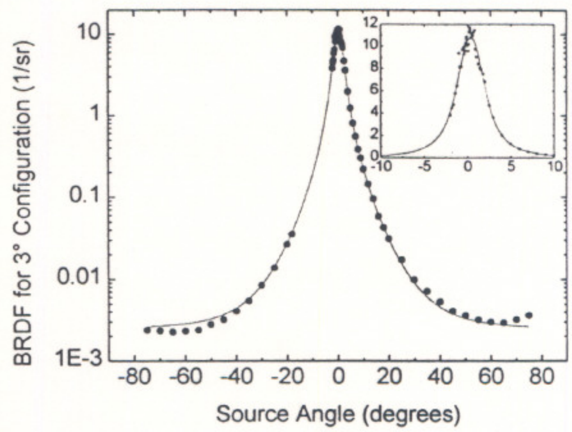

Fig. 6. BRDF of screen employed for model. Inset shows peak area of BRDF on a linear scale.

There are anticipated complications and further areas of research: (1) Wavelength dependence and polarization dependence must be addressed. (2) The possibility of the reflection properties changing as the pixels change their color or luminance must also be investigated. (3) A simplified method of extracting the BRDF parameters must be investigated. (4) Simple methods to account for non-symmetrical BRDFs must be developed (e.g., Eq. 7). (5) The complications arising from multiple separated surfaces with each surface having different reflection properties needs consideration. (6) Simple software tools need to be implemented to permit BRDF calculations for displays. (7) Simple verification methods must be developed.

REFERENCES

[1] G. Jones, E. Kelley, T. Germer, "Specular and Diffuse Reflection Measurements of Electronic Displays," Society for Information Display International Symposium Digest of Technical Papers, Vol. 27, San Diego, CA, pp. 203-206, May 12-17, 1996.

[2] F. E. Nicodemus, J. C. Richmond, J. J. Hsia, I. W. Ginsberg, and T. Limperis, "Geometrical Considerations and Nomenclature for Reflectance," NBS Monograph 160, October 1977.

[3] Private communications with Michael Becker. There is a precedent for using "haze" for this quality of reflection. See the ASTM specification for haze measurement of gloss paints: ASTM D 4039-93 "Standard Test Method for Reflection Haze of High-Gloss Surfaces."